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FROM: J. Douglas McCuistion, Chairman, Planetary Mission Senior Review 2016

TO: Dr. James Green, Planetary Sciences Division Director, NASA Headquarters

SUBJECT: Report for Planetary Mission Senior Review 2016

Dr. Green,

The 2016 Planetary Mission Senior Review (PMSR-16) was conducted over 2 weeks, May 16-18 for Solar System Exploration missions and May 23-26 for Mars Exploration missions. In total nine missions were reviewed: New Horizon's Kuiper Belt Extended Mission (KEM), Lunar Reconnaissance Orbiter (LRO) and New Dawn in week 1; Mars Science Laboratory/Curiosity, Mars Exploration Rovers/Opportunity, Mars Reconnaissance Orbiter (MRO), Odyssey, Mars Express (MEx), and Mars Atmosphere and Volatile EvolutioN (MAVEN) in week 2. Whereas membership of the two panel's was largely different, two members (in addition to the Chairman and the sponsor's Program Executive) were carried between the 2 weeks to assist in balancing and leveling of scoring processes and results.

The reviews went extremely well and all missions did a commendable job of proposal development, responding to Panel questions, and interacting with the Panel at the face-to-face meetings. The primary focus of the panel meetings was for the missions to respond to proposal questions from Panel members submitted in advance, as well as provide updates to mission's technical or scientific status. The Panel paid careful consideration and adherence to the proposal and evaluation criteria delineated in the *Guideline Narrative for Planetary Mission Senior Review Science Evaluation*, dated 15 Jan 2016, Planetary Science Division, NASA Headquarters. It is important to note that an extended mission proposal for Dawn was not expected and therefore not identified in this document for evaluation; however the Panel considered the proposal that Dawn did submit under the same criteria as all other missions. It is also important to note that missions and their science value were not compared to each other, but were evaluated only on their own individual merit per the *Guidelines*. The Panel voted on each mission individually. Adjectival scores are reported below with a brief summary of each proposal and the Panel's findings. Individual Summary Evaluations for each mission are in Attachment (1).

All proposals, just like their primary missions, are unique but two proposals stood out—KEM and MRO—with exceptionally well developed science strategies, opportunities for new discoveries, and above average proposal quality. Several Mars missions perform programmatic functions such as relay communications for surface assets (Curiosity, Opportunity, and future missions), landing site characterization, etc. These programmatic functions were neither considered in evaluation nor in the scores for extending any of these missions. There are also opportunities for inter-mission synergies in similar or collaborative measurements, both for current and upcoming missions (e.g. MAVEN and MEx), which were evaluated. Most missions had reduced budget guidelines from previous years and therefore reduced mission scope. Proposed overguides and descopes were dealt with very differently mission-to-mission. The Panel requested that all missions provide science budget breakdowns to allow evaluation of actual research and analysis being performed, which was evaluated in scoring. Since most reductions,

whether guideline or descope driven, are taken out of science it is critical to evaluate the balance of science performed compared to technical/operations risk being accepted.

The Panel voted based on the proposals, the questions answered in advance, presentations at the face-to-face, questions answered from the presentations, and Panel deliberations. In only one case was a re-vote deemed necessary, and that was for New Dawn, therefore the Chair reconvened the Solar System Exploration panel on June 2nd by telecom (discussed below).

Extended Missions (EM) are highly efficient dollar/value missions and the Panel unanimously believes that all should be approved for extension. The Panel is confident that the return on investment for these EMs will be significant—"changing the textbooks", inspiring new scientists and engineers, and leading to deeper understanding of the unsolved mysteries of the Solar System as well as new insights to life here on Earth. The compelling science that convinced the Agency to invest in the mission initially has been accomplished through Level 1 requirements and mission success criteria, but an even greater return on investment is embodied by the ability of these missions to continue exploring for a fraction of the cost and risk of building and launching a new mission. EM's often yield unexpected ground-breaking discoveries that lead to different, more informative missions as well as shaping future Decadal Survey strategies. In ever-tightening NASA budgets these efficiencies need to be exploited to maximize value for the taxpayer and scientific community. These extended missions are important contributors to planetary science, thus the Panel approached the reviews with appropriate earnestness taking scientific, science implementation (technical), and budgetary factors into account.

Summaries of the Panel's findings and scores follow, in alphabetical order:

Curiosity/Mars Science Laboratory—Very Good.

Curiosity presented a well-crafted proposal with few weaknesses, and very good correlation to Decadal priorities. The Extended Mission 2 (EM2) continues Curiosity's traverse from its present position at the base of Aeolis Mons (Mt. Sharpe) upward through ever-younger stratigraphy. In EM2 the science objectives will continue: geologic context, diversity of habitable environments (including preservation of organics), and evolution of the atmosphere and climate. It will conduct geological, geochemical and mineralogical measurements along its upward ascent that address these objectives. Units to be investigated during EM2 include the upper Murray Formation, Hematite Ridge, and the lower portion of the Clay Unit, yet Curiosity will not reach the clay/sulfate boundary in this extended mission (which was proposed in EM1).

The rover, its instruments, and the Science Team are well positioned to conduct the proposed research with significant opportunities for ground-breaking science and new discoveries. Features/complications of an aging rover are being well managed by the Operations Team. The pace of the traverse up Aeolis Mons may not allow Curiosity to reach the higher stratigraphic units that are of most scientific significance until well into EM3. The Panel unanimously found that the highest probability of ground-breaking discoveries is, therefore, at risk, especially given the forecast degradation in power in EM2 (15-30% reduction) and other risks (e.g. life-limited SAM pumps, short in the percussive section of the drill, deteriorating wheels, etc.). The Panel found that characterization of higher stratigraphic units in EM2 should be a prime objective. Curiosity did not believe an overguide was required and the Panel agrees, however the descope option traverses even more slowly up Aeolis Mons, which the Panel found to be unacceptably delaying investigation at higher elevations on Aeolis Mons especially with EM3 being forecast to be operationally limited due to degraded power levels.

DAWN—Good/Fair (145 Adeona).

The Panel was pleased that DAWN submitted an Extended Mission (EM) proposal unexpectedly.

The last minute determination of a viable extended mission required rapid proposal development/submission to meet the PMSR deadline, therefore eliciting a significant number of questions from the Panel prior to the face-to-face. This is the only mission that required the Panel to revisit initial voting and scoring.

The EM proposes to leave Ceres in July 2016 and conduct a slow flyby of 145 Adeona, a 150-km Ch-class asteroid, in May 2019. The proposed Adeona EM provides an opportunity for compositional mapping and improved knowledge of the surface age from another dark C-type asteroid, a class of asteroids about which relatively little is understood. Some en-route measurements would be taken, e.g. background calibrations of the X-ray channel of the GRaND instrument to help with Ceres measurements already taken. This plan also reduces the risk of losing another reaction wheel if they remain at Ceres as wheels are not needed in this Adeona EM. Proposed science during Adeona flyby includes mapping most of the surface at < 5 km/pix and some at < 200 m/pix. As an alternative to ending the mission, continuing measurements at Ceres was mentioned briefly, which prompted the Panel to request information on this as a descope (as required by the *Guidelines*), which was evaluated by the Solar System Exploration Sub-panel on 2 June 2016 by telecon. The descope proposal keeps Dawn at Ceres to continue observations in Low Altitude Mapping Orbit (LAMO) for an additional 9-12 months, doubling the time in LAMO. This would improve GRaND's hydrogen mapping signal/noise, double high-spatial-resolution spectral coverage of the surface, and increase the resolution of topographic maps in interesting regions. Either EM is an unanticipated lien on the Planetary Science Division's extended mission budget; Adeona's proposed cost is roughly $21.6M; the descope Ceres mission is roughly $9.6M (after carry-in in both cases).

The Panel found that visiting a new small body (Adeona) always has the potential for unanticipated, ground-breaking discoveries; yet remaining at Ceres does as well in compositionally interesting regions. Many discrepancies in the Adeona proposal were undoubtedly due to the hurried nature of its development, and the Panel found it lacking science traceability, specifics and justifications. For example, it did not clearly defined how the New Dawn objectives address Decadal questions and there is no direct link made between "Goals" in the Traceability Matrix and the Decadal, or indeed where the "goals" came from. Most critically lacking was a comparison of science achievable between Adeona and remaining at Ceres (requested via the descope). Additionally, the Panel was concerned about Dawn having achieved all Level 1 requirements prior to departing Ceres. The project response to this Panel question indicated that the results of the hydrogen mapping are not yet clear, and remaining at Ceres would lead to a 1.5x improvement in neutron signal/noise for hydrogen, an important issue in tracing water in the solar system.

The Panel voted on both the Adeona and the Ceres descope at the face-to-face meeting (without detailed descope information); Adeona scored GOOD/FAIR, Ceres scored VERY GOOD/GOOD. These scores were unchanged after detailed review and discussion of the descope option at the 2 June 2016 telecon. Considering both options, risks of instrument and spacecraft capability, and proposal budgets, the Panel found that the descoped mission to stay at Ceres had the potential to be more scientifically valuable than the proposed Adeona mission (as reflected in the scores). The Panel also found that there are likely mission modifications to preserve the life of instruments and spacecraft if there is a desire to extend at Ceres longer than 12 months. In summary, considering overall science value, extended mission budget constraints, and other budget-related findings of this PMSR Panel, continuation at Ceres is the more valuable option if the Planetary Science Division decides to continue the mission.

Lunar Reconnaissance Orbiter (LRO)—Excellent/Very Good.

LRO submitted a strong and soundly constructed proposal for EM3, called the *CornerStone Mission*, with excellent detail for the Panel to properly assess and evaluate the proposed mission and science. EM3 extends the measurements of existing instruments and expands their utility through a

combination of new operations modes, orbit evolution and collaborative measurements. The larger themes of contemporary, evolutionary and fundamental processes are clearly traceable to Decadal Survey goals and are highly important to lunar and planetary science (diurnal variability of volatiles, cratering, regolith development and maturation, etc).

The Panel found that EM3 offers a high potential for understanding key science questions, providing greater insight into distribution and quantity of volatiles on the surface, especially in permanently shadowed areas, solar wind and meteor stream sources of volatiles and their emplacement in polar cold traps, etc. The data acquired will be unique compared to previous measurements and will be used to address the three main themes of the *CornerStone Mission*. The Panel found that the proposal overall would have been strengthened further by a clearer development of, and emphasis on, coordinated instrument observations and how this approach would yield even more unique and important discoveries. This is likely a remnant of LROs formulation as a "measurements" mission under Human Space Flight that transitioned to a science-based mission. The Panel found it commendable that LRO has increased (slightly) science budgets in EM3 even in the face of an overall budget reduction without adding measureable risk to operations (Table 3), however LRO's reserve posture is not identified in the proposal and should be understood by the Planetary Science Division. Neither the overguides nor descopes were considered necessary or prudent.

New Horizons—Excellent.

The Kuiper belt Extended Mission (KEM) was one of the two most compelling and well-crafted EM's. The mission would perform a close flyby of a cold classical Kuiper Belt Object (KBO) MU69 in 2019 while collecting spectroscopic and image data to study its composition, volatile content and evolution, surrounding environment, as well as investigate any potential ring structures or satellites. Two separate trajectories are possible, 3000km pass and a 10,000km pass, which can be selected late in the trajectory for mission safety (similarly to the Pluto fly-by). Miscellaneous remote observations en-route would also be conducted of additional KBOs from various vantage points that are impossible to achieve from Earth. The EM is much longer than the traditional 2 year cycle due to trajectory time and data return, and therefore covers 2017-2021.

The Panel found that there were significant opportunities for ground-breaking science and new discoveries as New Horizons ventures into a truly unexplored region of the solar system that is nearly impossible to study otherwise. This extended mission adventure itself is a ground-breaking mission. This proposed EM is directly endorsed by both the 2003 and 2013 Decadal Surveys, as well as having an initial mission design to allow extended lifetime to accomplish such a mission deeper into the Kuiper Belt. The Panel found that neither the overguides nor descopes were considered necessary or prudent, however the Panel was disappointed to see leadership development for future Principal
Investigators and Project Scientists relegated to an overguide in the most expensive EM.

Mars Express (MEx)—Good.

MEx is a unique and challenging EM to review since it is a collaboration on a European Space Agency (ESA) mission, however the low score is a reflection on the quality of the proposal, EM6 science value and performance in past EMs. This sixth extended mission is focused on coordinated observations with MAVEN using the ASPERA, MARSIS, and MaRS radio occultation experiments over southern latitudes during perihelion. The proposal also presents subsurface sounding by MARSIS with substantially improved spatial resolution and a new ionospheric compensation algorithm enabling a 10x greater along-track spatial resolution.

Between being a series of US investigations on this European Space Agency (ESA) mission and the budget reductions over past extended missions, MEx more resembles a data collection mission than

a typical NASA science mission since there is almost no funding left for actual science research. The potential exists for ground-breaking science with planned MEx-MAVEN unique measurements in atmospheric physics, and stratigraphy and volatile inventory in polar layered deposits. However, neither usage of the acquired data sets nor how science analyses would be accomplished to attain Decadal goals was described adequately. The proposal lacked hypothesis-driven science questions and descriptions of how scientific investigations would be carried out. While data placed in the Planetary Data System (PDS) is well utilized by the larger community there is an unacceptably long delay between data collection and archiving for MARSIS, the last PDS deposit being 10 years ago from the MARSIS PI. The Panel found that the $3M budget generally seems to be out of line with MEx's qualitative *science value* to NASA, however the Panel recognizes that the overall data set and other programmatic support in this international collaboration is important to both NASA and ESA. By careful scrutiny of budgets (in greater detail than this Panel has been chartered to review) an increase in US science participation while remaining in-guide appears possible, which would make MEx's science value more commensurate to the Agency's investment. For example, the Panel found that the overguide request for the University of Iowa MARSIS data product project (in collaboration with MAVEN) would be worthwhile, but only if funded from within current guidelines. The Panel found that, since MEx is at the science floor, further reductions are unacceptable as they likely result in termination of PDS data archiving, US investigator science collaborations with MEx teams, and/or MaRS data losses. By the very nature of the project construct the proposal is choppy and hard to evaluate. Coupled with the current balance of science value to programmatic value, MEx's extended missions may be better suited to bi-annual *programmatic evaluation* by the Planetary Sciences Division rather than *scientific evaluation* through the Senior Review process.

Mars Reconnaissance Orbiter (MRO)—Excellent.

This is the other extremely compelling and well-crafted extended mission proposal, with the theme of *Mars in Transition*. The science objectives are broad, impacting almost all aspects of Mars science, including determining Mars habitability, assessing present Mars volatile inventories, monitoring surface changes (particularly those involving water), and monitoring present atmosphere and polar processes. EM4 searches for young aqueous deposits and carbonates, monitors RSL's, characterizes sulfate/phyllosilicate transitions, and addresses atmosphere goals to better understand inter-annual variations. The instrument teams have also developed new operational modes (e.g. stereo, along-/cross-track observations and SHARAD 3D processing algorithms) that had limited use in EM3 but offer excellent prospects for new discoveries in EM4.

The proposal showed a compelling breadth of science with impressive detail in tracing science guidelines to science floor, as well as high relevancy to Decadal objectives. The Panel found that there were significant opportunities for ground-breaking science and new discoveries, as well as an effective strategy to build on observations and measurements from EM3. The team is doing an impressive job of managing an aging asset and returning excellent science, e.g. managing Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) cryo-cooler limited life. MRO also boasts an impressive record of PDS deliveries, as well as extensive utilization of the data by a broad community, which increases the likelihood of science discovery. The only true negative is the uncertainty of SHARAD data delivery. Issues within the Italian Space Agency (ASI) are being worked by ASI, however recent deliveries have been problematic and require Agency-level attention to be responsive to community needs. MRO's important role in surface asset communication and landing site characterization was noted but not directly integrated into the scoring.

The Panel found that there is considerable value to gravity science provided by the overguide budget since long-term data records of change will enable a better tracking of seasonal gravity changes. However the Panel finds that, considering the significant reserve levels carried by MRO (>$800K/year), assuming reserves in FY17 are not exhausted, the utilization of $500K of FY18

reserves to support gravity science is a rational risk/reward trade-off in EM4. Descoping to the science floor was given significant attention considering the value of MRO science and deemed unacceptable. The Panel found that the science floor budget substantially limits the ability to target scientifically important sites and deteriorates MRO's powerful science suite, its opportunities for coordination with other missions, and seriously harms the breadth of MRO investigations and discoveries.

Mars Atmosphere and Volatile EvolutioN (MAVEN)—Excellent/Very Good.

This was MAVEN's first formal Extended Mission review, and the mission team presented a strong proposal with no major weaknesses. EM1 was a bridge from Phase E to extended mission phase. The EM2 proposal would support extended seasonal, inter-annual, and solar cycle/event temporal coverage for composition, energetics, fields, and dynamics from the lower thermosphere into the exosphere of Mars. A significant set of new measurements has been designed and demonstrated for EM2, e.g. coordinated MEx observations for correlation of upper level solar wind conditions, observations of ion outflow associated with remnant magnetic field regions, observation of neutral thermospheric winds, and a new set of deep dip observations. These observations support the broadest study of the Mars upper atmosphere to-date, characterizing long-term climate evolution on Mars.

The Panel found that there were significant opportunities for ground-breaking science and new discoveries in Mars atmospheric physics that cannot be accomplished with any other orbiter (including the ESA Trace Gas Orbiter (TGO), which will be more complementary science) and direct fulfillment of 2003 and 2013 Decadal Survey's recommendations for critical Mars investigations. EM2 will provide comprehensive observations of the Mars upper atmosphere and solar wind environment during a previously unobserved part of the solar cycle during a second Mars year. Additionally, critically important science can be done with synergistic measurements with MEx, ESA TGO, and possibly MRO. Neither the overguide nor descopes were found to be necessary or prudent. Note that MAVEN's second descope option reduced the mission to communications relay-only, which the Panel considered outside our purview to evaluate since this would be a purely programmatic decision.

Odyssey—Very Good/Good.

Odyssey provided a very viable and well thought out EM7 proposal that will extend science, and providing greater opportunity for new discoveries than in its previous EM's due to establishment in a new 6:45 AM/PM orbit, a geometry not achieved since Viking and with now new instruments. New investigations include studies of recurring slope lineae, volatiles, dust deposits, surface layering, and atmospheric phenomena. Other investigations include the search for volcanic hot spots and possible observations of the Martian moons. The spacecraft is remarkably healthy and the Operations Team is doing an excellent job of managing this aging asset.

The Panel found that the new 6:45 AM/PM orbit enables observations that could contribute to new and unique ground-breaking science investigations. THEMIS will continue as a very productive instrument that returns significant, unique science (imaging at high spatial resolution for the mid-IR), but the linkage of investigations to the search for life was generally not convincing due to limitations in its spectral and spatial resolution. Proposed coordinated observations with other spacecraft (MSL, MRO, MAVEN) have the potential to return important science, such as coupling between the lower and upper atmosphere. The proposal did not demonstrate that the search for volcanic heat sources would yield tangible results. The usefulness of GRS data (HEND/NS) to the broader scientific community was not demonstrated. The Panel found that the value of two more years of HEND/NS data was neither fully justified nor commensurate with the work proposed to monitor and validate data for the PDS. At more than 10% ($395K/year) of the science payload

budget, and the proposal/Project stating explicitly that no science analysis from HEND/NS would be conducted, this funding could be better utilized in areas such as enhancing science team research, adding participating scientists, and/or expanding collaborations with other missions (e.g. MAVEN and MRO). This finding is similar to Odyssey's PMSR-14 Report finding. Neither the overguide nor descopes were considered necessary or prudent (the overguide was not well justified especially with $200K/year in reserve funding), and if a descope were indeed to be implemented THEMIS support must be preserved over HEND/NS.

Opportunity/Mars Exploration Rovers—Excellent/Very Good.

The 10th Extended Mission proposal is a very compelling EM driven by significant opportunities for ground-break science and new discoveries at Endeavour Crater. It is extremely well focused with 3 objectives directly traceable to high priority science of the Decadal Survey. Opportunity will take advantage of the rover's unique location in and around Endeavour crater, an ancient Noachian environment that holds evolutionary clues to Mars geochemistry and represents a promising epoch to study from the perspective of habitability. The centerpiece of the EM10 is exploration of a small gully. In Endeavour's lower elevations the team expects to find evidence of ancient alteration under neutral pH rather than acidic conditions, the opportunity to observe changes in the aqueous chemistry over time, and contributions of flowing water to gully formation.

The Panel found that a focused and achievable program is proposed with well-defined targets and strong coordination with orbital data. Fundamental science questions are addressed, and there is great potential for new discovery, especially in exploration of the gully. The proposed science program is an excellent use of the remaining capabilities of the rover. Even with a degraded rover this team maximizes the science achievable while operating with no budget reserves. After 9 extended missions the eroding budget requires the operational planning cycle to be reduced. This continual budget erosion has also nearly eliminated important educational and training opportunities for students and post-docs. The Panel found that with the potential for ground-breaking new discoveries along Endeavour crater, the aging rover, reduced operations tempo, and reduced science participation, were of great concern. The Panel consensus was that this mission is at the science and mission-safety/engineering floor so a descope would be irresponsible. It was also a consensus finding that a modest overguide proposed ($1.8M/year) is a highly desirable investment to restore the EM-9 cadence of planning cycles to enable valuable science, reduce operational risk and improve science and operational robustness, which can negate unforeseen delays in progress towards the three critical EM10 scientific objectives. This will help ensure the proposed ground-breaking science is not forfeited after the extended traverse from Victoria crater.

It has been a pleasure and a privilege to Chair this Extended Mission review. The Panel composition was outstanding, yielding lively and thoughtful deliberations for such an essential topic. I am at your disposal to discuss the findings of the Panel as you deem appropriate.

Regards,

J. Douglas McCuistion
Chairman, PMSR-16

Attachment:
(1) Summary Evaluations for each mission